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A DOUBLE GAMMA-RAY SPECTROMETER TO SEARCH FOR POSITRONS IN SPACE

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SUMMARY

The features of scintillation counting techniques allow the development of detectors which can be made to respond preferentially to chosen types of particles. One series of experiments requires the development of detectors which will identify single positrons mixed in a relatively high flux of other radiations in space. Directional detectors of positrons having energies between a few ev and a few Mev have been designed to search for admixtures of these particles in the cosmic radiation near the top of the atmosphere, in the electron population of the trapped radiation zone, and in the solar particle streams and plasma clouds in interplanetary space. These detectors, which are scheduled for flight on balloons, sounding rockets, and the Eccentric Geophysical Observatory satellite, are described in this report. The scintillation techniques involved are discussed and the analog and digital data-recovery instrumentation for each experiment is outlined.

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A DOUBLE GAMMA-RAY SPECTROMETER TO SEARCH FOR POSITRONS IN SPACE*

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INTRODUCTION

A study of the intensities of positrons in interplanetary space and in the earth's radiation zone should provide knowledge about the processes occurring there. Positrons can be created only by interactions involving at least one Mev of energy. They are created in nuclear interactions through the beta decay of excited nuclei, and also in very high energy nuclear interactions through the double decay of pi mesons. High energy photons and electrons, when passing through sufficient material, create positrons by means of shower production.

Thus, the existence or absence of positrons in a certain medium will indicate the extent to which high energy interactions are involved in the production of the particle population. For example, there is a flux of positrons emerging from the upper atmosphere which is created by interactions of primary cosmic rays with air nuclei. The electrons forming the plasma above the atmosphere are, however, the result of the ionization of ordinary matter. Therefore a knowledge of the intensity of positrons in the earth's radiation zone might provide some information about the acceleration of these trapped electrons. Also, solar protons that are incident on the top of the atmosphere produce excited positron-emitting N and O nuclei which may, in turn, inject positrons into the trapped radiation by their decay. A study of the variations of the positron intensity in the radiation zone at the time of the arrival of solar protons may be useful in understanding the formation of the trapped particle zone. On the basis of a background calculation it is estimated that it should

*This paper was presented at the Eighth Scintillation and Semiconductor Counter Symposium, Washington, March 1962; it will be published in *IRE Transactions on Nuclear Science*.

be possible, with the experiments outlined in this report, to measure positron-to-electron ratios as low as 10^{-6} in the radiation zone. The possible arrival of low energy solar or interplanetary positrons at the edge of the earth's magnetic field also is open to experimental investigation. Since the energy sensitivity of the detector, which will be discussed later, extends down to a few ev, the background should be of such a nature that it will be possible to measure positron-to-proton ratios as low as 10^{-10} in the interplanetary plasma; this measurement would thereby provide information about the very low energy particle population in the interplanetary medium which is pushed out in the solar wind. If solar protons are accompanied by positrons we would also learn more about the question of the production of these high energy particles and their relation to the interplanetary magnetic field. Finally, it is not known whether particles with energies of a few Mev can penetrate the inner solar system near the time of solar minimum; if they can, the low-energy tail of the galactic positron flux should be detectable.

THE EXPERIMENTAL PROGRAM

Our program is to search for positrons in interplanetary space and the radiation zone, and to study the various intensities and their changes in time if these are indeed measurable. Three experiments have been developed during the last year for three specific studies.

First, a small positron detector with an energy sensitivity between a few ev and 2 Mev was designed for use in the interplanetary medium beyond the earth's magnetosphere; this device is scheduled for flight in 1963 on the Eccentric Geophysical Observatory (EGO) satellite. It will explore the existence of interplanetary and solar positron fluxes. Throughout the course of each orbit the trapped radiation zones will also be sampled. The satellite's lifetime is expected to be as long as one year, permitting time variation studies to be made.

Second, a similar positron detector is scheduled for a single flight into the outer radiation zone in mid-1962 on a 4-stage Argo D-8 sounding rocket. The experiment will provide background information relevant to the EGO experiment and should provide a good measurement of the quiet-time positron admixture in the particle population of the outer radiation zone. The detector to be used for this experiment differs from the EGO device only in the use of faster data-sampling rates and a small shield intended to reduce the background effects of the intense low energy particle fluxes. Both differences are possible because the rocket can carry greater weight and can use wider-band telemetry per experiment.

The third experiment uses a telescope capable of measuring the ratio of electron-to-positron intensity as a function of energy. It was designed for flight on high-altitude balloons. The device has an extended energy sensitivity, up to about 15 Mev, and will measure the energy spectrum of the electrons and positrons produced at the top of the atmosphere by the primary cosmic radiation. Detailed knowledge of the electron and positron fluxes from such origins, as well as knowledge of the population of the radiation zone, will be useful in interpreting the results of the EGO experiment. It may also be possible to derive preliminary information about the intensity of high energy positrons in the primary cosmic radiation.

THE POSITRON DETECTOR

The nature of the interactions of positrons determines the detection technique as a function of energy. A positron may be described as having two unambiguous characteristics – its charge-to-mass ratio, and its annihilation reaction which occurs when it has been reduced to thermal energy in the presence of matter. Thus, one type of positron detector is an instrument that measures the q/m of incoming particles. A magnetic analyzer, which measures the momentum-to-charge ratio, coupled with an energy-loss measuring device, could be used to identify high energy positrons and, in fact, was used to make the discovery of positrons in 1932. A second type of positron detector, useful for lower energies and more suited to present spacecraft applications, detects the annihilation products — two coincident gamma rays, each having 0.51 Mev of energy -- rather than the positron itself. The positron must generally be stopped to be annihilated. Its kinetic energy can be measured as it comes to rest and the two gamma rays emerge "back to back" from the point of annihilation. This detection technique has the restriction that only positrons with energies below a few Mev can be detected with a minimum of background. Since the pair-production cross section increases with electron energy, higher energy electrons stopping in the detector are more likely to produce a secondary positron. This fact sets the upper limit of detectable energy; the lower limit of the energy of a detectable positron is a few ev, determined by the charge on the spacecraft.

The positron detector to be used on the EGO and the sounding rocket is illustrated in Figure 1. The sensitive elements of the positron detector consist of two cylindrical CsI (Tl) crystals, each completely embedded in a block of scintillating plastic. These two phosphor sandwich or *phoswich* units are optically separated. A third small CsI (Tl) crystal rests at the bottom of a conical well which is machined in the joined scintillator blocks. The scintillators are all enclosed in an aluminum can to which three photomultipliers are attached. Two of the photomultipliers view the bottom surfaces of the outer composite scintillators and the third views the central CsI crystal through a light pipe composed of a plastic scintillator optically separated from the other two phoswich units. The thickness of this crystal limits the kinetic energy of incident positrons to about 2.5 Mev; minimum-ionizing particles of greater energy penetrate to the anticoincidence case. Each photomultiplier receives the integrated light output of the composite scintillator which it sees. Discrimination against particles entering any of the plastic scintillators is accomplished by circuitry which uses the phoswich technique to sense the rise time of the light pulses.

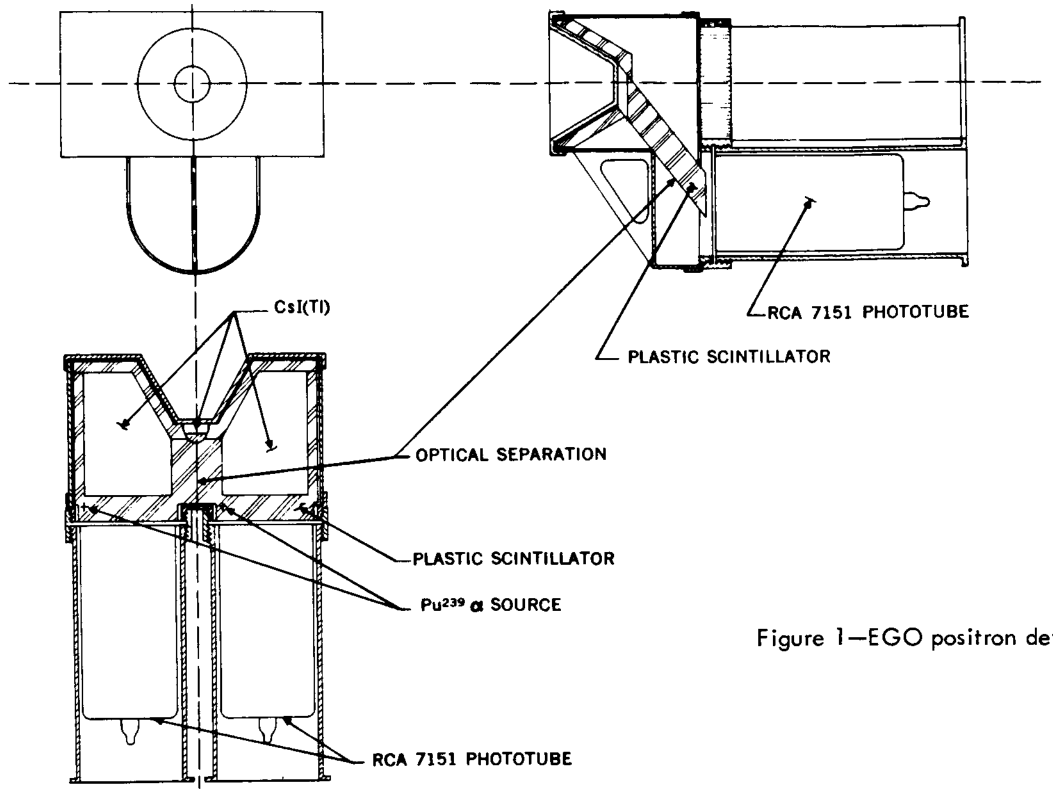

Figure 1—EGO positron detector

This guard counter assembly minimizes the likelihood that a combination of other particles will simulate a positron event.

Positron identification signals are generated in three ways. The first method is to require two coincident gamma rays of characteristic energy to emerge, 180 degrees apart, from the central scintillator, in which a third coincident loss of energy also takes place. The second method of identification, with relaxed criteria which allow a somewhat higher detection efficiency, is to require that a single characteristic gamma ray be in coincidence with an incoming stopped particle. The third method, necessary for identifying nonpenetrating positrons, is to require the two coincident characteristic gamma rays to emerge 180 degrees apart from an inert annihilating block. In the spacecraft-borne detectors, all three of these modes will be used in order to maximize the amount of information related to the measuring of the incident positron flux and to determine the background corrections. In all of these cases the incident flux is collimated and required to stop by the encasing scintillators used in anticoincidence.

SCINTILLATION COUNTER TECHNIQUES

The phoswich technique, introduced by Wilkinson (Reference 1) and applied by Jones to gamma-ray spectrometers (Reference 2), has a limit of useful dynamic range, a limit imposed by the fast fluctuations in the slowly rising CsI charge pulse and by the frequency response of the silicon transistors (which are required for temperature stability and low power drain in most spacecraft applications). In spite of this limited dynamic range (perhaps a factor of ten) for comparison of current pulses, successful rejection of fast pulses is possible. A minimum of 0.8 Mev of energy is lost by a charged particle penetrating the plastic scintillator; in spite of the non-uniform light collection and the different scintillation efficiencies, the resulting current pulse which is due to this plastic output is much greater than those which are due to differentiated CsI pulses that correspond to energy losses in the region of 0.5 ± 0.4 Mev.

The application of photomultiplier tubes and scintillators outlined here involves certain other considerations. Contours of the sensitivity of the cathode of the ruggedized 7151 phototube have been mapped with results similar to those of Widmaier (Reference 3); histograms of the sensitivities of small areas of equal size reveal a spread of up to a factor of five with a full-width half-maximum of about half the total spread. In addition, the proximity of the source of gamma rays (the anticipated annihilation inside the detector) results in poorer resolution than would be obtained in detecting a parallel-incident beam of gamma rays. Consequently the resolution of the 0.51 Mev peak in a phoswich assembly of the configuration used does not approach the ideal; however, sufficient photopeak resolution has been obtained to permit the detector's use as a double gamma-ray spectrometer in a real sense.

Phototube gains have been observed to change on a number of satellites and space probes after the first pass or several passes through the radiation zone. In each case a stabilization followed at a new gain value. This effect is thought to be due to fatigue of the sort studied by Cathey (Reference 4) which may have been produced by the prolonged and intense light output of the scintillating crystal immersed in the radiation zone. The phototubes will be exposed prior to launch, and it is hoped that this will minimize the shift.

Inflight calibration is an important consideration, since gain instability of the scintillator, phototube, amplifier, pulse conditioner, and transmitter ensemble may arise from a variety of causes. An inflight calibration which is independent of such instabilities consists of comparing the measured pulse height spectrum with another pulse height spectrum produced in the same device by nearly monoenergetic particles. In each spectrometer an alpha-particle source is attached to the plastic scintillator. The Pu^{239} alpha-particle light output in the plastic scintillator is reduced by saturation effects to the equivalent of about 1/4 Mev, the relative pulse heights depending on the circuit time constants and relative light collection efficiencies in the phoswich. Since they lose energy only in the plastic scintillator, the calibration alpha particles will be prohibited, by the anticoincidence feature, from contributing to positron or gamma-ray simulating events.

In summary, the search for positrons will be conducted by transmitting the pulse-height outputs of the two spectrometers, when the various coincidence-anticoincidence requirements are satisfied, in order to display the presence or absence of coincident 1/2 Mev lines. And the spectrometers will be calibrated in flight through the transmission of the pulse spectra measured by the individual counters, including the alpha-particle spectra, by using the same spectrometer electronics and relaxing the coincidence-anticoincidence requirements at certain intervals.

DETECTOR SELECTIVITY

Since there is no knowledge of the positron fluxes in interplanetary space or in the radiation zone, it is important to insure that the false counting rates of the detectors are kept as low as possible. The detectors will encounter a background of cosmic radiation, trapped particles, occasional solar proton fluxes, and the low energy particles of the interplanetary plasma clouds; thus, false events from a variety of causes will arise. For example, higher "single" counting rates than can be accepted will occur in the interior of the radiation zone; positron-emitting excited carbon and aluminum nuclei will be produced in the material of the detector by incident protons; locally produced shower positrons and random coincidences of 1/2 Mev gamma rays due to nearby positron annihilations will form a residual background. To minimize these effects, for example, the lowest acceptable voltages will be used on the phototube dynodes; a short time-resolution coincidence circuit will be used; and the EGO detector will be mounted with a minimum of material nearby. The sounding rocket detector will be shielded, to allow a greater penetration into the radiation zone. Also, prior to launch, the detector will be subjected to beams of artificially accelerated protons in order to determine some of the background corrections directly and to compare the positron-emitting characteristics of the bombarded beryllium and aluminum detector material.

Estimates of the upper limits of a detectable positron flux in each of the cases described above have been made (not presented here) on the basis of the available information about particle fluxes in space and on more fragmentary information about the reaction products of nuclear interactions. For example, the present estimate of the lowest measurable positron-to-electron ratio in the radiation zone is 10^{-6}; the lowest measurable positron-to-proton ratio in the plasma of interplanetary space should be about 10^{-10}; the lowest measurable positron flux in deep space should be about $10^{-3}/cm^2$-sec.

INSTRUMENTATION

A reduced block diagram of the electronics to be used by the EGO and the sounding rocket detectors is shown in Figure 2. (A full description of the electronic circuitry is being prepared for publication.) The pairs of pulse heights from the two gamma-ray spectrometers will be transmitted when the gate is applied with an accuracy of up to 1/256 in the case of the EGO satellite and of about 1/50 in the case of the sounding rocket. The

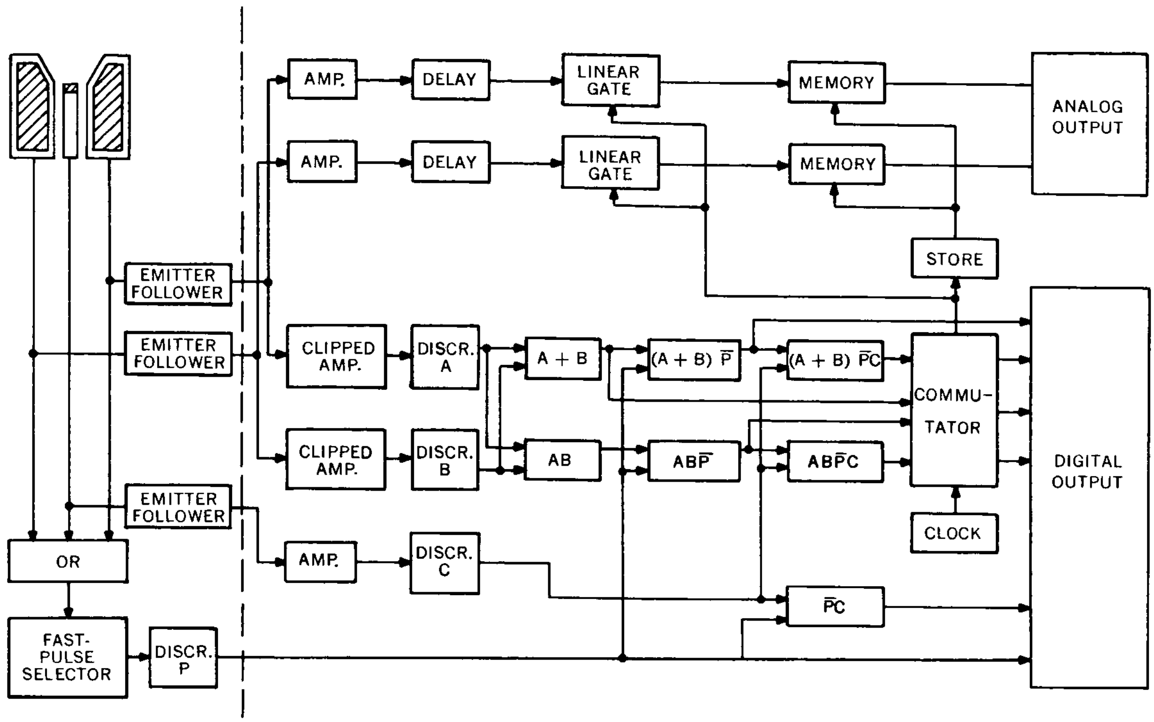

Figure 2—Block diagram of positron detector

four ways of generating this gate will be used for alternate and equal intervals of time: (1) A single event used for purposes of calibration; (2) a threefold coincidence between all CsI crystals with no output from the plastic scintillator, corresponding to a positron giving rise to gamma-rays detected in both spectrometers; (3) a twofold coincidence using either CsI gamma-ray detector and the central crystal; and (4) a twofold coincidence between the two gamma-ray detectors, corresponding to a positron of insufficient energy to penetrate into the well of the detector. The maximum rate at which both the pulse heights will normally be transmitted by the EGO is once per second; by the sounding rocket, once per millisecond. However, the rates at which these gates are generated, as well as the rates of other relevant single events, will be transmitted with a wide dynamic range of up to 2^{16}/second in both cases. Knowledge of the rate of single events in each counter and of the various combinations will extend the useful dynamic range of the detectors.

THE POSITRON TELESCOPE

A positron "telescope" (Figure 3) will be balloon-borne for the purpose of providing auxiliary data about secondary positrons in the upper atmosphere. This detector selects electrons and positrons from the total incident flux by comparing the rate of energy loss in the upper scintillator with the total energy loss recorded in the lower, and by the

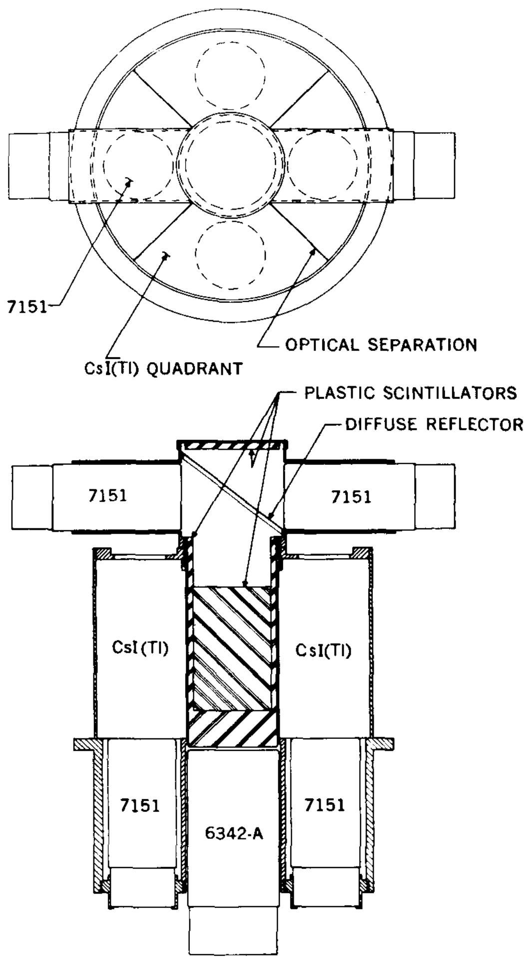

Figure 3—Positron "telescope"

requirement of no energy loss in the guard counter.* Positrons are then separated from electrons (with a certain efficiency) by the detection of one or two events of 0.5 ± 0.25 Mev energy loss in any one or two surrounding CsI crystals. A plastic scintillator rather than cesium iodide is used in the total energy counter to minimize electron-positron pair production by the detected electrons. Since the particle background at the top of the atmosphere is less intense than that in the radiation zone or in deep space, and since the positron flux there is expected to be higher, the requirement of mono-energetic gamma-ray detection can be relaxed. However, since the flight will be short, and accurate knowledge of the positron-to-electron ratio over a wide energy interval is desired, the efficiency will be greatly increased by the use of the four large adjacent CsI crystals.

It is required that the telescope be accurately calibrated. Calculations were made with an electronic computer to determine the positron separation efficiency, as a function of positron penetration into the total energy counter and of bias setting of the gamma-ray windows of the crystals (Figure 4). The curves for single and double gamma-ray detection labeled "minimum" are for the case of detection of a photoelectron, or a Compton scattering event resulting in a photoelectron, due, respectively, to either and both of the emerging gamma rays. "Maximum" indicates detection of all Comptons and photoelectrons; "calculated" indicates an intermediate bias setting. Calculations for an infinitely dense crystal material, indicated as "geometrical", are shown for comparison. Isotropy of the emerging pairs of oppositely directed gamma rays originating from uniformly distributed annihilating centers was required in all calculations, and losses in the plastic scintillator were included. These curves allow us to determine the efficiency as a function of energy from a measurement of the efficiency at one energy obtained, e.g., below the Pfotzer maximum. Comparison of the number of single and double gamma-ray events should give an indication of the background encountered; inflight calibrations of the gain settings of the

*For further information on the ΔE vs. E technique, refer to "A Scintillation Counter Telescope for Charge and Mass Identification of Primary Cosmic Rays," Bryant, D. A., Ludwig, G. H., and McDonald, F. B., a paper given at the Eighth Scintillation and Semiconductor Symposium, Washington, March 1962; to be published in *IRE Transactions on Nuclear Science* and as a NASA Technical Note.

two energy-loss detectors will be possible by comparison with minimum-ionizing events registered by the device.

A reduced block diagram of the electronics to be used in the balloon-borne experiment is shown in Figure 5. A gate generated by coincident events in the energy-loss and total-energy detectors will allow the magnitudes of both pulses to be recorded on tape by means of two 32-channel analyzers. A signal which is due to an event corresponding to greater-than-threshold energy loss in the guard counter that is coincident with this event will be registered; a coincident signal from the 0.5 ± 0.25 Mev window of each crystal will also be registered by the tape recorder. Since the background is not expected to be intense, the single rates of this detector will not be monitored.

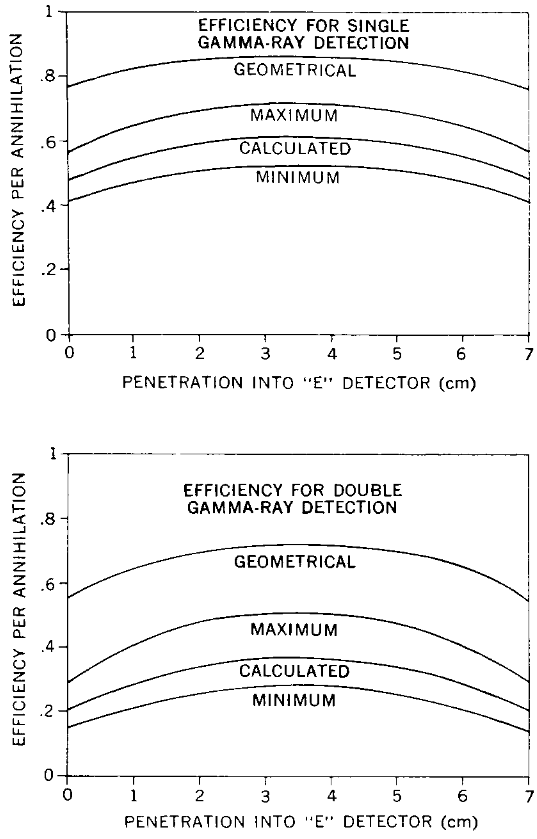

Figure 4—Positron separation efficiency of the positron "telescope" for single and double gamma-ray detection

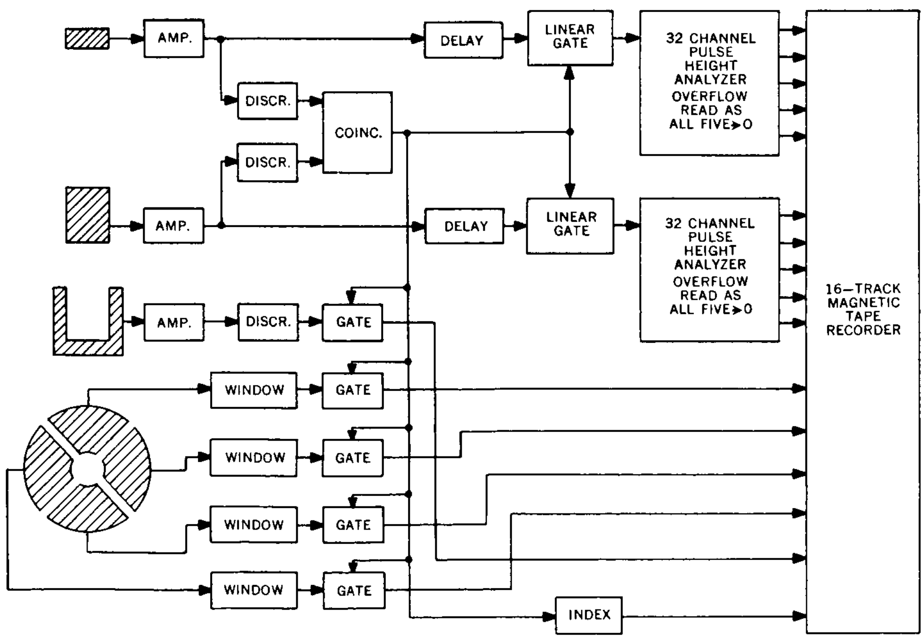

Figure 5—Block diagram of balloon-borne positron "telescope"

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It is a pleasure to thank Dr. Frank B. McDonald for his assistance in implementing these experiments. A number of people assisted in the development of these detectors. Mr. Guido Porreca designed most of the electronics for the EGO and rocket experiments, and Mr. Ciro A. Cancro supplied most of the electronics for the balloon-borne experiment. Mr. Adam G. Thompson and Mr. Howard Burns assisted in the mechanical design of the detector assemblies.

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